Electron Handedness in a Material

A new framework for studying chiral materials puts the emphasis on electron chirality rather than on the asymmetry of the atomic structure.

By **Hendrik Bentmann**

Chirality is a fundamental feature of nature, manifesting across scales—from elementary particles and molecules to biological organisms and galaxy formation. An object is considered chiral if it cannot be superimposed on its mirror image. In condensed-matter physics, chirality is primarily viewed as a structural asymmetry in the spatial arrangement of atoms within a crystal lattice [**1**]. A perhaps less familiar fact is that chirality is also a fundamental quantum property of individual electron states [**2**]. Now, Tatsuya Miki from Saitama University in Japan and colleagues introduce electron chirality as a framework to quantify symmetry breaking in solids, focusing on chiral and related axial materials [**3**]. The researchers propose a way of measuring electron chirality with photoemission spectroscopy. This new perspective on chirality may open pathways to discovering new functional properties in asymmetric materials.

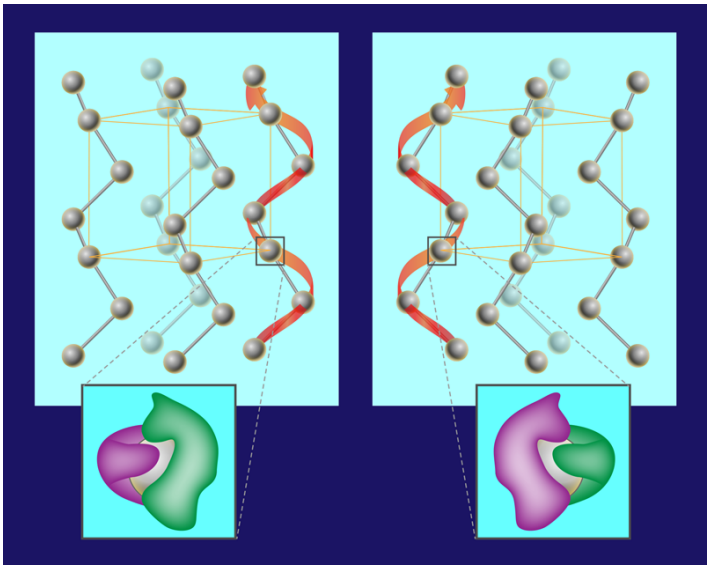

Figure 1: The atomic structure of tellurium (Te) can exhibit right-chiral or left-chiral crystal structure. The electrons in the material can also exhibit chirality based on the relative orientations of their spin and momentum. The insets show the spatial distribution of electron chirality around a specific Te atom, where green corresponds to right chirality and purple corresponds to left chirality.
Credit: APS/Alan Stonebraker

A familiar example of a chiral object is the human hand: left and right hands cannot be superimposed and are mirror images of each other. Fundamental particles such as the electron can also exhibit chirality, based on the so-called parity transformation in quantum field theory [**2**]. This mirror-like operation relates two chiral states—a left-handed state and a right-handed state—which behave differently under the weak force. Left-handed electrons, for example, have weak interactions, but right-handed ones do not. A property closely related to chirality is helicity: the projection of the spin onto the direction of momentum. In the case of massless fermions, helicity and chirality states coincide.

In condensed-matter physics, chirality is primarily viewed as a structural asymmetry. A chiral arrangement of atoms is one that breaks certain symmetries—specifically, "improper" symmetries that include reflection and inversion [**1**]. The study of chiral materials has a vivid and longstanding history. In 1848, Louis Pasteur observed the double sodium-ammonium salt of tartaric acid under a microscope and noticed two types of crystals, each a mirror image of the other. When dissolved in

water separately, each solution rotated polarized light in opposite directions—the first observation of optical activity arising from chirality in molecular structure.

Fast forward to the 21st century, researchers continue to be interested in chiral materials, especially in how the chirality of their crystal structure affects electronic and spin properties. For example, recent experiments demonstrated that a chiral material can act as an efficient source of electron-spin polarization, an effect known as chirality-induced spin selectivity (CISS) [**4**]. Chiral crystals also exhibit unconventional band-structure topologies and surface states [**5**]. More recent work established a connection between chirality and orbital texture—the arrangement of electronic orbits in reciprocal (momentum) space [**6**, **7**].

These examples highlight a top-down view in which chiral structure imparts chiral behavior on electrons. However, chiral electron states may arise in achiral crystals. Weyl semimetals with broken inversion symmetry, for example, are achiral, and yet they host quasiparticles that behave as massless Weyl fermions with specific handedness [**8**]. This electronic chirality is encoded in the momentum distribution of Berry curvature—a property of the Bloch wave functions that acts as a magnetic field in reciprocal space [**9**]. This rich phenomenology motivates a bottom-up approach, in which electron chirality is considered as an intrinsic property of a material.

Miki and colleagues establish electron chirality as a microscopic degree of freedom in a material, alongside the more traditional degrees of freedom that are charge, spin, and orbital motion. The chiral state of an electron—its "handedness"—is described as the projection of the electron's spin along the direction of its momentum. Some electrons in a material are left-chiral, some right-chiral, but most are a mixture of the two. The researchers consider the chirality density, a position-dependent quantity that represents the difference between right-chiral and left-chiral contributions to the charge density. Furthermore, they introduce the axiality density as the difference between right-chiral and left-chiral contributions to the electric polarization.

Equipped with this framework, they perform first-principles calculations for the chiral material tellurium (Te) and the ferroaxial material $K_2Zr(PO_4)_2$. Ferroaxial order is akin to ferroelectricity but instead involves a rotational structural distortion. The calculations reveal characteristic spatial distributions of electron chirality within the crystal unit cell, related to the chiral and axial lattice symmetries. Going further, the authors compute the energy dependence of the spatially averaged electron chirality, which may be regarded as the difference between right-chiral and left-chiral contributions to the density of states (DOS). For Te, the energy dependence of this chirality-resolved DOS shows rapid variations and sign changes, indicating that a chiral material with a left-handed structure may contain predominantly left-chiral or right-chiral electrons, depending on microscopic details of the material (Fig. **1**). Changing the chirality of the crystal from left- to right-handed, however, also swaps the electron chirality.

The team proposes a way of experimentally probing electron chirality using circular dichroism in angle-resolved photoelectron spectroscopy (ARPES). ARPES, in which radiation is used to liberate electrons from a material, provides energy and momentum information about individual Bloch electron states in the band structure of a crystal. In circular dichroism, the input radiation is circularly polarized, allowing more information to be gathered about these Bloch states. This method has been previously used to probe the chiral properties of quasiparticles in a Weyl semimetal [**10**].

Miki and colleagues compute the ARPES response for the chiral material CoSi and find a correspondence between the momentum-resolved circular dichroism and electron chirality. The results provide a promising connection to recent ARPES experiments on CoSi in which chirality-induced circular dichroism was observed [**6**]. Nevertheless, at this stage, the relation between circular dichroism and electron chirality remains to be explored in more detail. While the latter derives from the electron spin, the former is typically considered to reflect the orbital degree of freedom—at least within the dipole approximation—potentially complicating a direct correspondence. Adding spin resolution in the ARPES measurement might open an additional experimental pathway toward probing electron chirality.

Chiral materials—and more generally materials with reduced symmetry—are of particular interest because they display functional properties, such as ferroelectricity, piezoelectricity, and nonlinear optical behavior. These materials also have the

potential to exhibit new phenomena that could drive emerging fields, such as spintronics and orbitronics. The results by Miki and colleagues pave the way for an improved analysis of how lattice symmetries in these systems affect electronic properties at the microscopic level. This will aid the exploration of new functionalities and phenomena in asymmetric materials. An interesting future direction is to extend the framework to magnetic materials, which could yield insights into the relation between electron chirality and noncollinear spin configurations.

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